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Subsidence history analysis and forward modelling of the Cape and Karoo Supergroups

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ABSTRACT: In the southern Cape region, the Cape and Karoo Supergroups can be subdivided into two provinces comprising the Western Cape province and the Southeastern Cape province; their differences reflect a variable tectonic history. A synthetic model, derived by sequential backstripping of the stratigraphy is presented, quantifying the amount of tectonic subsidence within these two provinces. Two episodes of accelerated subsidence, starting at about 465 and 390 Ma respectively, are recorded in the Cape Supergroup in both provinces. Extension (β) factors range between 1.10 to 1.20, and 1.06 to 1.14, for the first and second episodes, respectively. There is considerable variation in the degree of extension along the preserved strike of the Cape Basin during both episodes. A third period of accelerated subsidence records the onset of the Karoo Supergroup. Along-strike variations in the southern Karoo basin subsidence suggest a large component of in-plane compressive buckling of lithosphere whose rheology was altered by the two preceding stretching phases.

1 INTRODUCTION

The sediments of the Cape and Karoo Supergroups (Fig.1) represent a 300-million-years history of nonmarine and shallow-marine deposition along an evolving section of the palaeo-Pacific margin of Gondwana during the Palaeozoic and early Mesozoic (de Wit and Ransome, this volume). The evolution of this section of Gondwana's margin, and the transition from the Cape basin to the Karoo basin, are still poorly understood. It is generally believed that the transition marks the inversion from a rift-subsidence, "Atlantic-type continental-margin basin" (Cape Supergroup) to a compressional "Andean-type continental-foreland basin" (Karoo Supergroup; de Wit and Ransome, this volume).

The siliciclastic sediments of the Cape Supergroup were deposited onto a Precambrian-Cambrian basement which includes the Cape granitoid batholiths. The age of the Cape Supergroup ranges from the early Ordovician (circa 500 Ma) to the early Carboniferous (circa 330 Ma). These rocks are continuously exposed for nearly 1000 km along the southern tip of Africa (Figs. 1 and 2a). The stratigraphy is summarised in Table 1, whilst a more detailed account of the stratigraphy and sedimentary record is given by Broquet (this volume).

The base of the Karoo Supergroup is dominated by the glacigenic deposits of the Permo-Carboniferous Dwyka Group, which overlies the Cape Supergroup para- to unconformably (Visser, this volume; Cole, this volume). A detailed overview of the stratigraphy and a sedimentological analysis of the Karoo Sequence is given by Cole (this volume). The stratigraphy of the Karoo Sequence is summarized in Table 2; and the areal distribution of stratigraphic units is shown on Fig. 2b.

In the southern Cape region, two sub-basinal environments have been recognized in both the Cape Supergroup and the Karoo Supergroup. These sub-basins are, today, separated by the Syntaxial Domain of the Cape Fold Belt (de Beer, this volume; Ransome and de Wit, this volume), and are referred to as the Western Cape and Southeastern Cape provinces in this paper (Fig. 1).

In this contribution, we attempt a

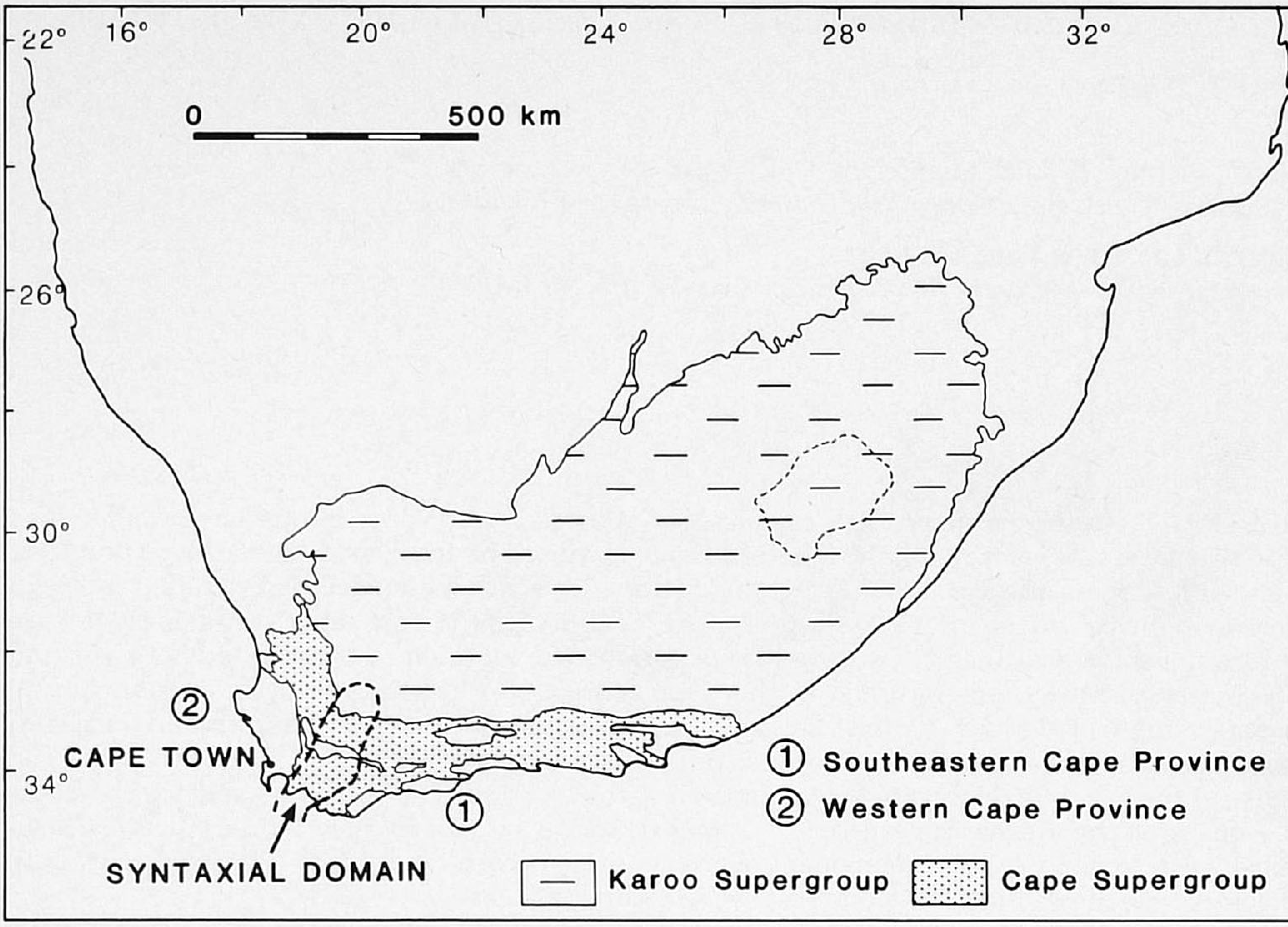

Figure 1 Map of southern Africa showing the regional distribution of the Cape and Karoo Supergroups and the position of the two main sub-depositional centres (provinces) referred to in this paper.

quantitative analysis of the published stratigraphic and sedimentological data from the Cape and Karoo Supergroups, and construct a first order model for the tectonic subsidence history of this part of Gondwana's Palaeozoic Pacific margin. In order to achieve this, the stratigraphic records from both these major sedimentary sequences are backstripped using procedures described below. Forward modelling of the subsidence is then applied to quantify extensional and compressional phases of the basins' evolution.

2 SUBSIDENCE ANALYSIS

The backstripping procedure removes the effect of sediment loading from the basement subsidence, thus allowing quantification of tectonic basin subsidence. Backstripping is performed by sequential removal of the uppermost layer and decompaction of the underlying strata. The amount of decompaction is calculated using empirical porosity/depth relations for the specific lithologies of each layer. Homogeneous local isostatic behaviour of the lithosphere is assumed. The input required for this computation is stratigraphic data specifying: sediment-type; age; thickeness; and petrologic characteristics bearing on porosity / depth relations as well as density for each lithology (c.f. Kooi and Cloetingh, 1989; Peper and Cloetingh, 1992). The data collated for this modelling of the western and southeastern Cape province are summarised in Tables 1 and 2. No account of fluctuations in paleobathymety have been incorporated in the modelling, since these may be largely controlled by variations in the ice-volume covering this part of Gondwana in the Palaeozoic. Two well recognized glacial

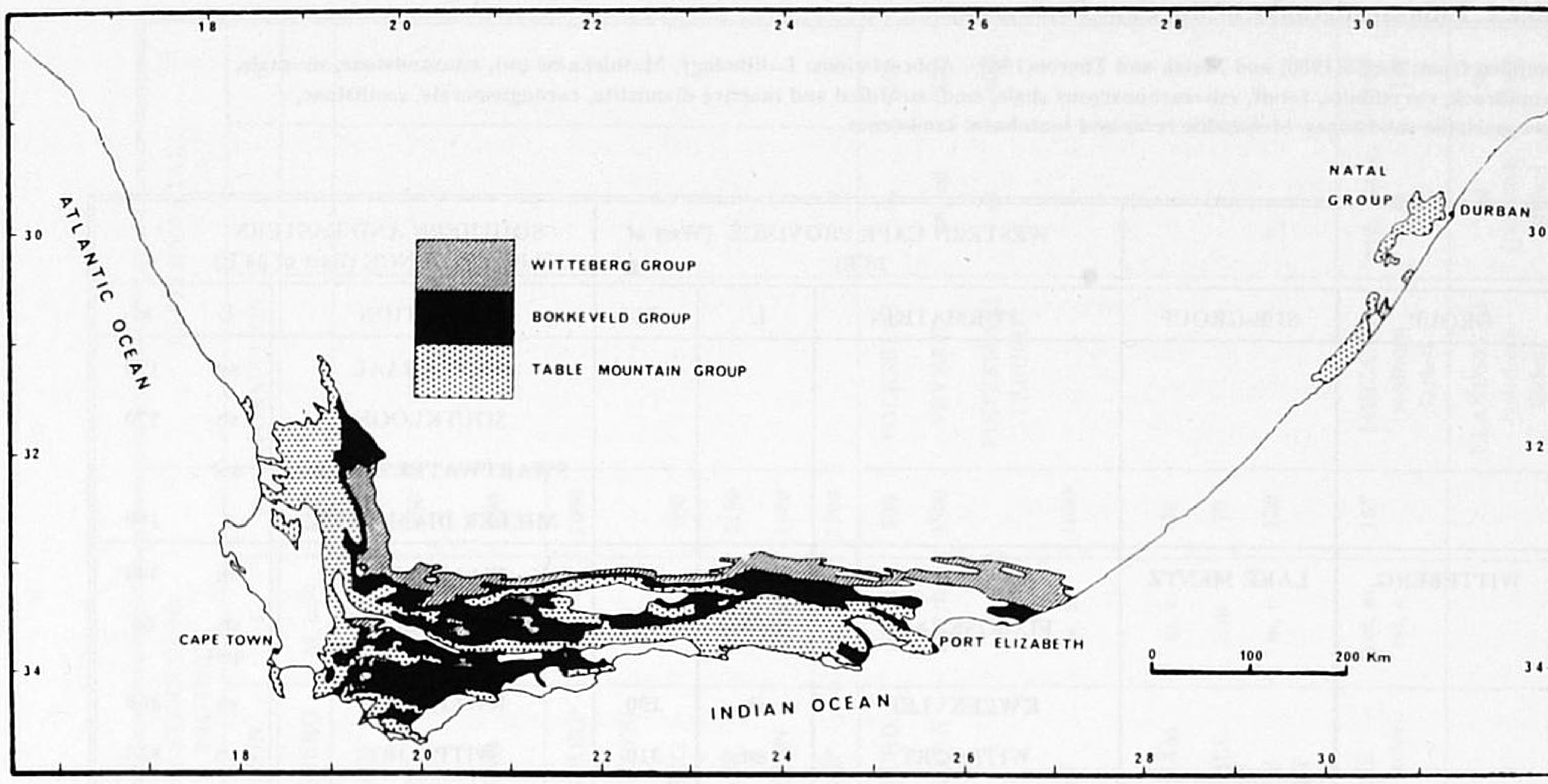

Figure 2a Regional distribution of the major Groups of the Cape Supergroup. Note that the sequences of the Table Mountain Group equivalents near Durban (the Natal Group) have not been incorporated in this work (modified from Theron and Loock, 1988).

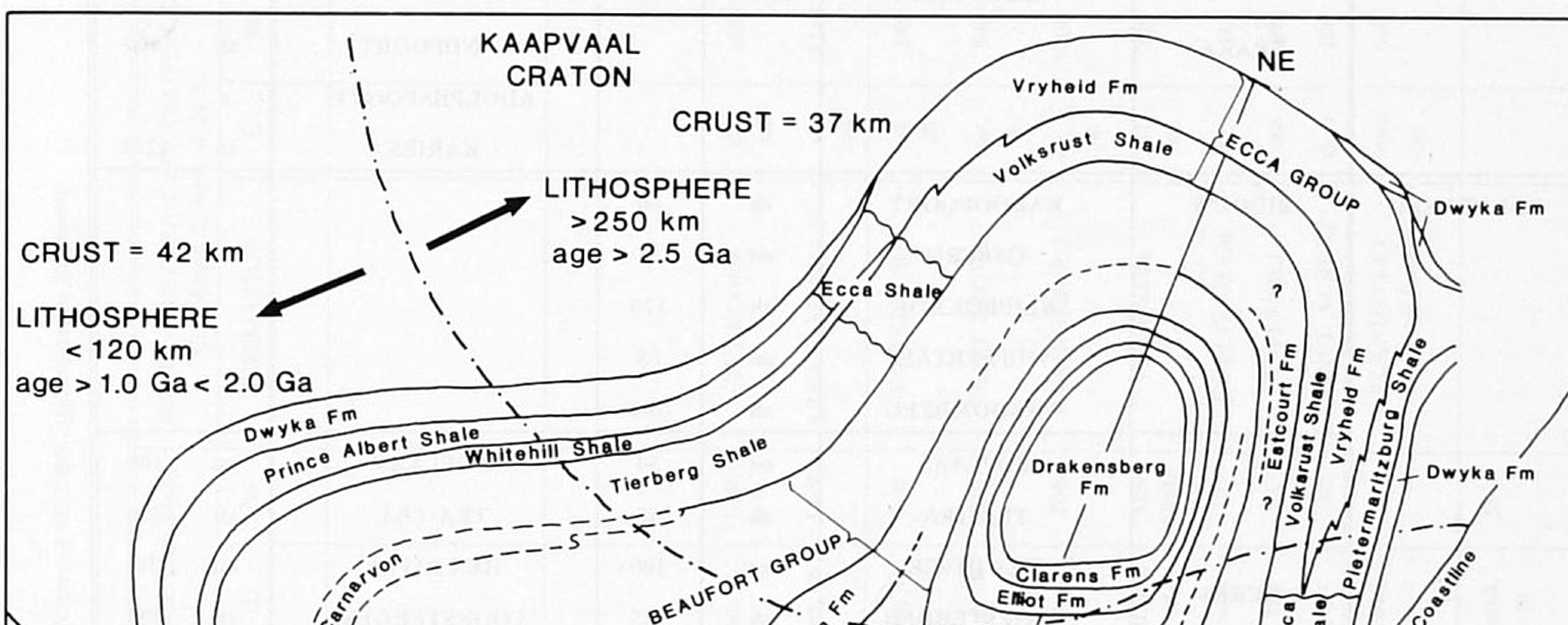

Figure 2b Schematic representation of the Karoo basin, showing the lateral extent of the stratigraphic units referred to in Tables 1 and 2. Also shown is the location and orientation of the Syntaxis and the two Ecca Sub-basins flanking this Syntaxis. Modified from S.A.C.S. (1980). An approximte NE-SW section, as shown, can be found in Cole (this volume). The crust/lithosphere thicknesses are taken from de Wit (this volume).

Table 1. Lithostratigraphy of the Cape Supergroup.

Complied from: SACS(1980) and Malan and Theron(1989). Abbreviations: L=lithology, M=thickness (m), sst=sandstone, sh=shale, m=mudrock, r=rythmite, t=tuff, csh=carbonaceous shale, smd=stratified and massive diamictite, c=conglomerate, s=siltstone, qsst=quartzitic sandstones, bl=basaltic lavas and bsst=basal sandstones.

		WESTERN CAPE PROVINCE (West of 20°E)			SOUTHERN AND EASTERN CAPE PROVINCE (East of 24°E)		
GROUP	SUB-GROUP	FORMATION	L	M	FORMATION	L	M
					DIRKSKRAAL	sst	110
					SOUTKLOOF	sh	170
					SWARTWATERSPOORT	sst	
					MILLER DIAMICTITE	d	100
WITTEBERG	LAKE MENTZ	WAAIPOORT	sh	?	WAAIPOORT	sh	340
		FLORISKRAAL	sh, qsst	60	FLORISKRAAL	sh, qsst	80
		KWEEKVLEI	sh	130	KWEEKVLEI	sh	200
		WITPOORT	sst	310	WITPOORT	sst	850
	WELTEVREDE	SWARTRUGGENS	sh, sst	450	WELTEVREDE	sh, sst	800
		BLINKBERG	sst	80			
		WAGEN DRIFT	sh, sst	70			
	TRAKA				SANDPOORT	sh	400
					ADOLPHSPOORT	s	
					KARIES	sh	1200
BOKKEVELD	BIDOUW	KAROOPOORT	sh	50			
		OSBERG	sst	55			
		KLIPBOKKOP	sh	170			
		WUPPERTAL	sst	65			
		WABOOMBERG	sh	200			
	CERES	BOPLAAS	sst	30	BOPLAAS	sst	100
		TRA-TRA	sh	85	TRA-TRA	sh	350
		HEX RIVER	sst	100	HEX RIVER	sst	70
		VOORSTEHOEK	sh	115	VOORSTEHOEK	sh	300
		GAMKA	sst	135	GAMKA	sst	200
		GYDO	sh	160	GYDO	sh	600
TABLE MOUNTAIN	NARDOUW	RIETVLEI	sst	150	BAVIAANSKLOOF	sh, sst	200
		SKURWEBERG	sst	255	SKURWEBERG	sst	345
		GOUDINI	sst	120	GOUDINI	sst, s	255
		CEDARBERG	sh	120	CEDARBERG	sh	50
		PAKHUIS	sst, c, d	40	PENINSULA	sst	1500
		PENINSULA	sst	1550			
		GRAAFWATER	sst, sh	440			
		PIEKENIERSKLOOF	c, sst	800			

Table 2. Lithostratigraphy of the main Karoo Basin.

Compiled from: Beukes(1970), SACS(1980), Cole et al.(1990) and Visser et al.(1990). []=maximum thickness
Abbreviations: see table 1.

		WESTERN CAPE PROVINCE (Sub-basin 1)			SOUTH WESTERN CAPE PROVINCE (Sub-basin 2, west of 24°E)			EASTERN CAPE PROVINCE			EASTERN NATAL		
GROUP	SUB-GROUP	FORMATION	L	M	FORMATION	L	M	FORMATION	L	m	FORMATION	L	m
LEBOMBO								DRAKENSBERG	bl, bsst	1380			
BEAUFORT								CLARENS	sst	300			
								ELLIOT	sst, m, sh	450			
								MOLTENO	sst, m, sh	600			
	TARKASTAD							BURGERSDORP (south of 31°36'S)	sh	1000			
								KATBERG	sst	900			
	ADELAIDE	TEEKLOOF	sst, sh	1030	TEEKLOOF	sh, sst	1030	BALFOUR	sh, sst	2150			
								MIDDLETON	sh, sst	1500			
		ABRAHAMSKRAAL	sst, sh	1440	ABRAHAMSKRAAL	sh, sst	1280	KOONAP	sh, sst	1300			
ECCA		KOEDOESBERG	sst, sh	180	WATERFORD	sst, sh	180	WATERFORD	sst, sh	800	VOLKSRUST	sh	200
								FORT BROWN	sst, sh	1500	VRYHEID	sh, sst	500
		KOOKFONTEIN	sst, sh	330	FORT BROWN	sst, sh	500				PIETERMARI-TZBURG	sh	400
		SKOORSTEENBERG	sst, sh	200	LAINGSBURG	sst, s, sh	400	RIPON	sst, sh	1000			
		TIERBERG	m, sst, r	385 [700]	VISCHKUIL	sst, sh	300						
		COLLINGHAM	m, t	30	COLLINGHAM	m, t	30	COLLINGHAM	m, t	30			
		WHITEHILL	csh	50	WHITEHILL	csh	50	WHITEHILL	csh	70			
		PRINCE ALBERT	m, r	180	PRINCE ALBERT	m, r	180	PRINCE ALBERT	m, r	120			
DWYKA		MBIZANE (northern facies)	smd, m, c	95	ELANDSVLEI (southern facies)	msd, m	660	MBIZANE (northern facies)	msd, m, sst, c	185	MBIZANE (southern facies)	md, sst, c, m	145 (15)
		ELANDSVLEI (southern facies)	msd, m	580							ELANDSVLEI (southern facies)	md ()=Swart-Mfolozi	50 (160)

deposits, one in the Cape Supergroup (Pakhuis Formation) and one at the onset of the Karoo basin (Dwyka Group), justify this approach at this stage (for further debates on palaeobathymetry, see Broquet, this volume; and Visser, this volume). A much more detailed data-set will be required to detect the tectonic contributions to the paleo-waterdepth changes.

The backstripped subsidence curves for the western and southeastern Cape provinces are shown in Figs 3a and 3b. The curves demonstrate the existence of three episodes of accelerated subsidence. The first, starting at 464 Ma (here taken as the start Table Mountain Group - but see Broquet [this volume] for arguments that this should be more in the region of 500 Ma) and lasting until about 430 Ma (start of the Nardouw Group, Table 1), shows rapid initial subsidence, followed by a subsequent phase of slower subsidence. The second rapid subsidence episode, starting at 390 Ma (the start of the Bokkeveld Group, Table 1), lasts until 375 Ma (corresponding to the end of the Bokkeveld Group). This second rapid episode of subsidence is again followed by a long phase of slow subsidence. It appears from the subsidence-history diagrams that the timing of subsidence is the same for both the Western and Southeastern Cape provinces, although the amount of subsidence differs greatly between these provinces. In the Western Cape province, subsidence during the first accelerated episode is greater than the corresponding subsidence of the Southeastern Cape province. Subsidence during the second rapid subsidence-episode, however, is greater in the Southeastern Cape province. The third and last phase of subsidence acceleration starts in the Western Cape province at 290 Ma (about the start of the Dwyka Group), and in the Southeastern province at 275 Ma (about the start of the Ecca Group, Table 2). In the Western Cape basin, sedimentation ceases at 245 Ma (at the top of the Adelaide Subgroup, Table 2) whilst in the Southeastern Cape province subsidence continued until 208 Ma. This variable subsidence history is also reflected in the differences in the stratigraphy of the Beaufort Group for both provinces (Fig. 2; Table 2).

The subsidence acceleration of the first two episodes, at 464 Ma and 390 Ma are interpreted as the expression of extensional (mechanical-stretching) phases, whereas the decay in subsidence probably reflects thermal cooling phases (cf. the McKenzie model; McKenzie, 1978).

The third phase of rapid subsidence (from 290 Ma onward) has a magnitude of only 2-3 km. This is immediately followed by the first-recorded compressional deformation structures (cleavage and associated thrusts) in the Cape Fold Belt at about 278 Ma (Hälbich, this volume; Cole, this volume), which also affected the Karoo sediments (Hälbich, this volume). It is therefore likely that the third accelerated subsidence phase reflects a regional compressional event. This could be a phase of foreland compression, but the observed magnitude and wavelength of the depocenter are not characteristic for a typical thrust-loaded foreland basin. The preferred tectonic scenario involves a large degree of lithospheric buckling (c.f. Stephenson and Cloetingh, 1991) induced by in-plane compression acting on a lithosphere plate whose rheology is weakened by preceding stretching phases (Cloetingh et al. 1989).

3 FORWARD MODELLING

Subsidence within an extensional basin is accounted for, using the McKenzie model, by homogeneous stretching of the crustal underlying lithosphere. During the period of stretching, rapid subsidence occurs, due to mechanical thinning of the crust and lithosphere. Subsequent thermal cooling and lithospheric thickening induces further, slow subsidence. In our model we have modified the McKenzie model to allow for multiple, finite stretching phases and the incorporation of lateral heat flow. We have used this modified model to obtain an estimate for the amount of extension for each of the extensional episodes.

Important first-order parameters for the model are the thicknesses of the crust and the lithosphere prior to stretching. Pre-rift crustal thickness of 42 km and a lithospheric thickness of 120 km were inferred from seismic data available from the adjacent Namaqualand terrain directly northwest of the Karoo basin. (Green and Durheim 1990; see also Fig.1 of de Wit, this volume).

The forward modelling of the subsidence shows that the subsidence patterns of extensional phases of the Western Cape

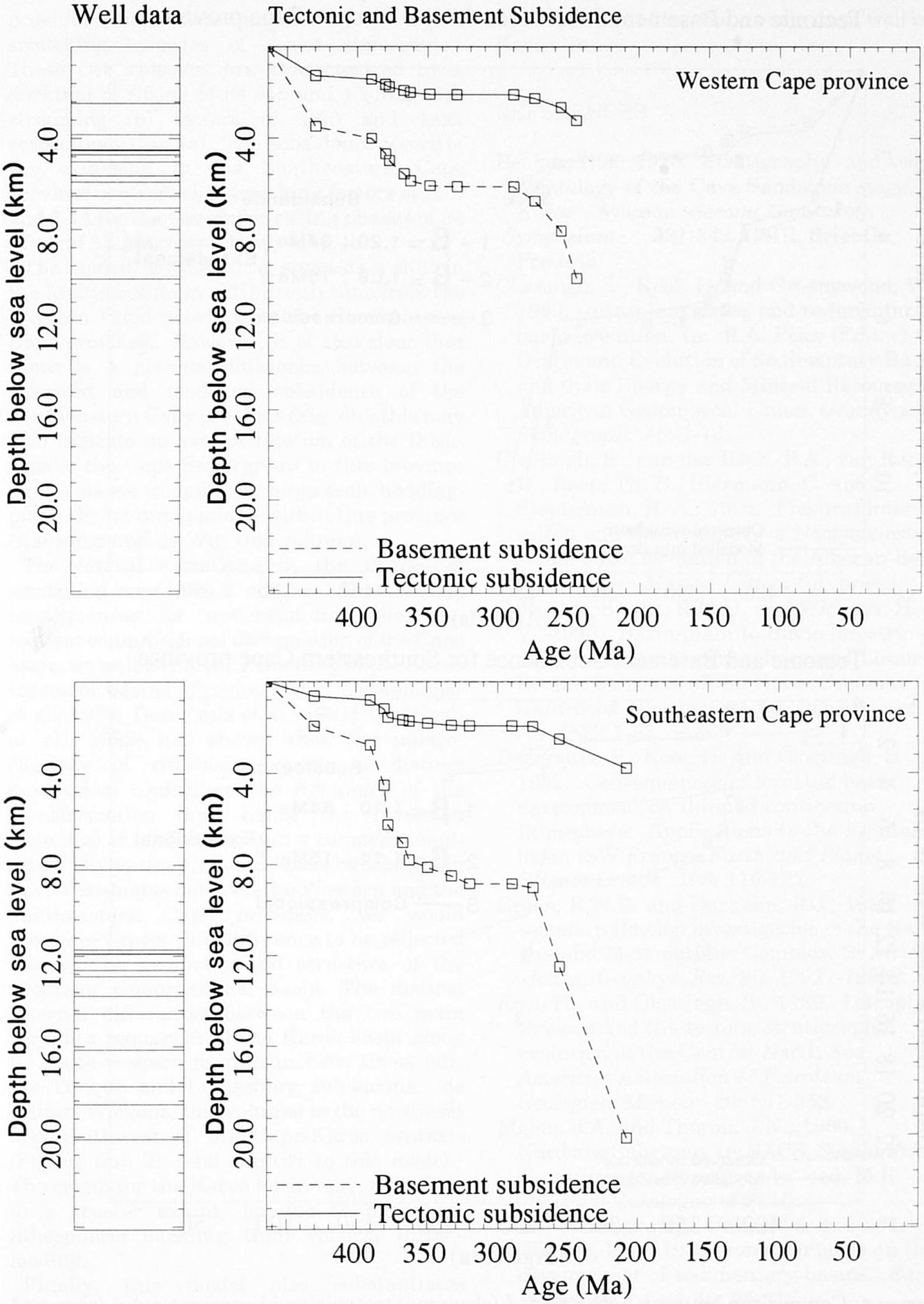

Figure 3 Backstripped tectonic and basement subsidence for the Western Cape province (a) and the southeastern Cape province (b).

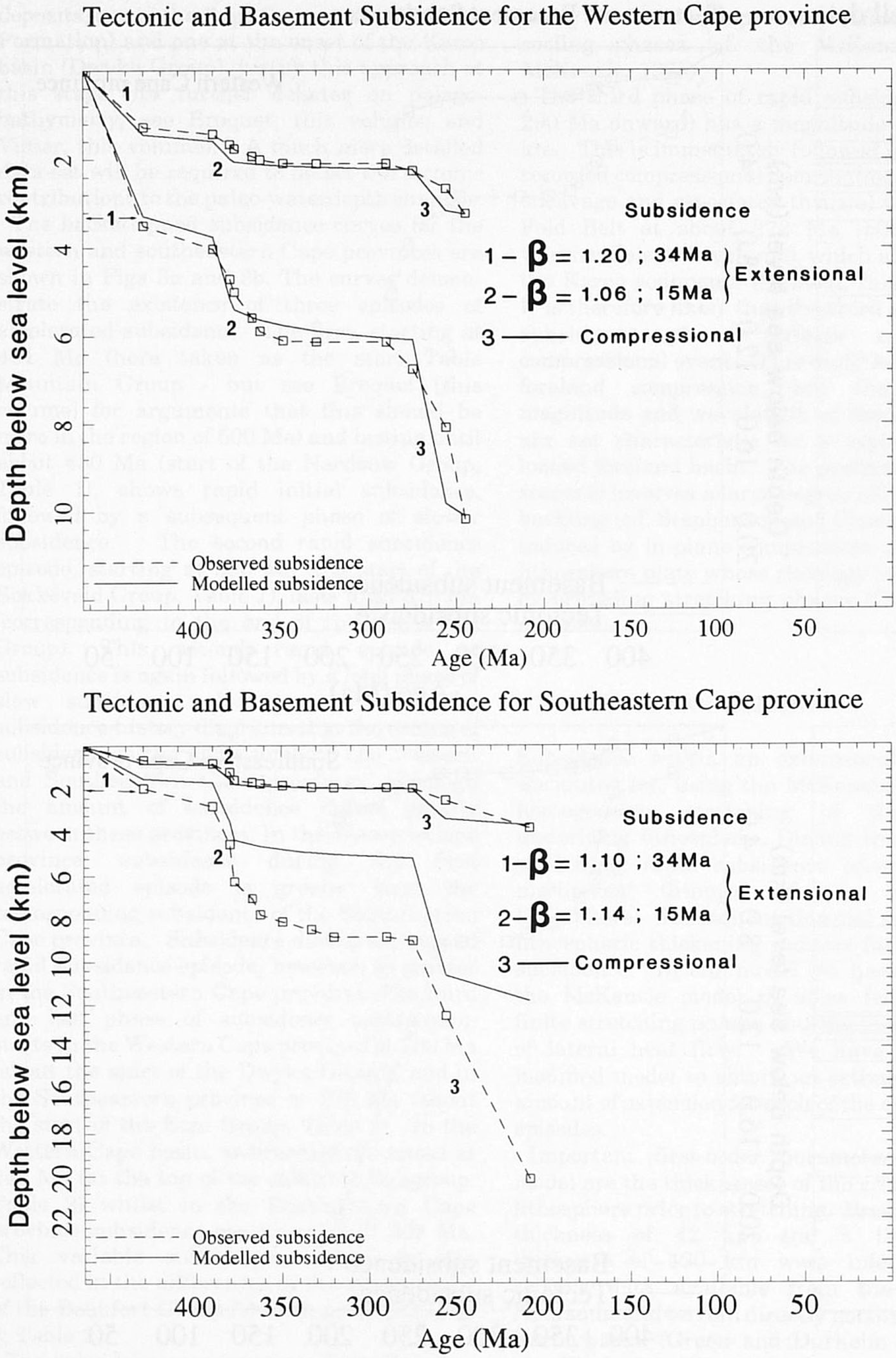

Figure 4 Comparison between backstripped (observed) tectonic and basement subsidence and modelled subsidence for the Western Cape province (a) and the southeastern province (b), adopting a uniform stretching model.

province can be accounted for by two finite stretching episodes of major significance. These two episodes are characterized by a duration of rifting of 34 Ma and 15 Ma, with stretching (β) factors of 1.20 and 1.06, respectively (Fig.4a). The subsidence record of the extension in the Southeastern Cape province contrasts by stretching factors of 1.10 and 1.14 for the two major rifting phases of 34 Ma and 15 Ma, respectively (Fig.4b).

The modelling, therefore, suggests a shift in the location of main rifting with time from the Western Cape province to the Southeastern Cape province. However, it is also clear that there is a notable difference between the observed and modelled subsidence of the Southeastern Cape province (Fig. 4b); this may well indicate an over-estimation of the thickness of the Cape Supergroup in this province due to, as yet undetected, large scale bedding-plane thrust duplications within this province (Ransome and de Wit, this volume).

The lateral variations in the degree of stretching may have a number of interesting consequences for understanding the subsequent compressional deformation of the Cape basin, as well as for the modelling of the Karoo successor basin. Previous work (Zoetemeijer et al., 1990; Desegaulx et al., 1991; Cloetingh et al., 1992) has shown that the palaeo-rheology of rift-basins exerts a distinct mechanical control on the dynamics of the transformation (and hence the inversion tectonics) of a rift-basin into a compressional-basin. Given the profound lateral variation in the β - estimates between the Western and the Southeastern Cape provinces, we would therefore expect this difference to be reflected also in the geometry and structure of the successor compressional basin. The distinct internal differences between the two main turbidite sequences of the Karoo basin along its south-western margin in Ecca times (viz. the Tanqua and Laingsburg sub-basins; de Villiers Wickens, this volume) to the northeast and southwest of the Cape-Karoo syntaxis (Figs. 1 and 2), lend support to this model. The origin for the Karoo basin may, therefore, to a greater extent, be due to horizontal lithospheric buckling than vertical thrust-loading.

Finally, this model also substantiates arguments that the Syntaxial Domain has been an inherited tectonic feature in the region from the start of the Cape basin until well into Karoo times.

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